Chapter 4
Description of Composite Materials

4-1. Terminology

a. An engineer who is not experienced in designing with FRP composite materials may not be familiar with many terms. Definitions of key terms will be found in the Glossary (Appendix D). Definitions of many key terms are also found in the ASTM standard listed below:

ASTM D 3878 Standard Terminology of High-Modulus Reinforcing Fibers and Their Composites

b. Over the years, the term *fiberglass* has been used to generically describe glass-fiber-reinforced-plastic products; for example, a *fiberglass* tank or a *fiberglass* boat. In precise terms, fiberglass is only describing the reinforcement fibers used in the composite product. However, the resin (plastic) matrix, in which the reinforcement fibers are embedded, is also an important component which greatly influences the mechanical and chemical resistance properties of the composite. Using an inappropriate resin for a given application could cause the component to perform poorly in its intended application or to prematurely fail. The acronym FRP has occasionally been used to denote fiberglass-reinforced plastic instead of just fiber-reinforced plastic. Current common usage is, however, to define FRP as fiber-reinforced plastic. Where identifying the fiber-reinforcement type is desired, a letter prefix may be added; for example, GFRP and CFRP to describe glass-fiber-reinforced and carbon-fiber-reinforced plastics, respectively. (See Appendix D for a further description of fiberglass.)

4-2. Background

a. General.

(1) In order to understand how composite materials perform in structures, it is necessary to understand some basics about their nature. Composite materials contain a mixture of two or more types of fundamentally different components. They have properties that are some combination of the properties of their components.

(2) All materials that contain more than one component are not necessarily composite materials. For example, pearlitic steel is not considered a composite, although it contains more than one component, since its various parts are of the same nature.

(3) Some materials that are considered composites are concrete, steel-reinforced concrete, fiber-reinforced polymers (like graphite/epoxy or glass/epoxy), laminated wood, and rubber tires. Concrete- and steel-reinforced concrete contain more than one type of component (aggregate, cement paste, and steel). Graphite- and glass-based FRP's contain high-strength fibers surrounded by a more ductile resin. Rubber tires contain the polymeric rubber-type material, carbon particles, and, frequently, steel or other types of reinforcement.

(4) The driving force behind the development of modern composite materials has been their high strength and stiffness when determined on a weight basis. Most of the original work on modern composites was in the aerospace industry. These industries are very weight sensitive, and a decrease in weight is a very important issue. This is the case even if the FRP parts are more expensive than the parts they replaced. Composites are now being used in the surface transportation industry. They are frequently used on automobiles and lightweight boats. Composites have also penetrated a number of consumer sports areas, such as graphite/epoxy golf clubs and skis.

(5) One way to better understand composite materials is to examine some current applications of composites. There are a number of aerospace applications. They are used as structural parts on many modern jet airplanes, such as the Boeing 767. The *Voyager* was the first airplane to fly around the world nonstop without refueling. Its superstructure was mostly made of composite materials. Similarly, the *Gossamer Albatross* became the first human-powered vehicle to fly across the English Channel. Such a vehicle could not be built with traditional metallic materials, for it would have been too heavy.

(6) Composites have also been used on land-based vehicles. For example, the auto industry has formed a consortium to do research on composite materials. They have successfully built a *Taurus* whose superstructure is composed of five composite panels that have been glued together. Glass-fiber-based composites have been used to form the hopper in railroad cars. The U.S. Army has recently designed and built an armored vehicle that has a composite material hull. The U.S. Navy has used composite materials to make mine sweeper ships.

(7) Composite materials are being used extensively in the sporting world. Glass-based FRP poles are commonly used in pole vaulting. Graphite/epoxy golf club shafts are highly desirable because of their light weight. Graphite/epoxy skis are also popular because of

their light weight. Glass-based FRPs have been used in small consumer-oriented sporting boats for many years.

(8) Composite materials are being used in civil engineering structures. The tentlike roof on the new Denver International Airport is made from a glass-based FRP that has been coated with Teflon. The same basic material has been used as the roof for a number of sports stadiums, such as the Metrodome in Minneapolis. Glass-based composites have been used in nearly 100,000 underground fuel storage tanks; this use is growing rapidly. Uses also include sandwich shell roofs for exhibition structures, large-diameter pipe, and numerous gratings and structural shapes.

b. Composite types.

(1) Particle based.

(a) There are two basic types of composites that use particle reinforcement. These two types are particle reinforced composites and dispersion-strengthened composites. Particle-reinforced composites use the particles to carry the major portion of the load. Dispersion-strengthened composites use the particles to resist deformation, while the resin carries the major portion of the load. Neither of these types of composites will typically be included in civil engineering applications, but a brief discussion is included for completeness.

(b) Particle-reinforced composites have hard particles surrounded by a softer matrix. The particles in these composites are larger than in dispersion-strengthened composites. The particle diameter is typically on the order of a few microns (a few ten thousandths of an inch). Typically the particles comprise between 20 percent and 40 percent (by volume) of the composite. In this type of composite, the particles carry a major portion of the load. The purpose of the resin matrix is to hold the particles together. Examples of particle reinforcement would be the addition of carbon black to automobile tires, and cermets (which are metal matrix composites with ceramic particle additions).

(c) In dispersion-strengthened materials, small particles on the order of 10 to 250 nanometers (10^{-9} m, which is less than a millionth of an inch) in diameter are added to the matrix material. These particles are smaller than the ones used in particle-reinforced composites. Up to 15 percent by volume of the material can be these particles. These particles act to help the matrix resist deformation. This makes the material harder and stronger. The matrix material is carrying most of the load.

(2) Fiber based.

(a) These are composite materials in which fibers have been added to increase the load-carrying capability of the material. The fibers may occupy anywhere from 40 percent to 70 percent (by volume) of the material. These fibers have relatively small diameters. For example, a typical graphite fiber diameter is on the order of 5 to 7 micrometers (10^{-6} m), while glass fibers are usually larger, on the order of 15 to 20 micrometers.

(b) The volume fraction of fibers has a significant effect upon the composite's mechanical properties. For details, see Chapter 5.

(c) Short fiber composites are fiber-based composites in which the fibers have been cut into short lengths and are randomly oriented throughout the material. These fibers are still long with respect to their diameter. The fibers are randomly mixed into the polymeric matrix. This type of composite will tend to have isotropic mechanical properties (which make it easier to design), but it means it is not as stiff nor as strong as it could be if the fibers are oriented. Complicated cast shapes can be made from this type of composite, when the resin is heated in the liquid region. The presence of the fibers will increase the viscosity of an already viscous liquid.

(3) Effect of fiber orientation.

(a) Fiber orientation will have a dramatic effect upon the mechanical properties of a fiber-reinforced composite material. Fibers can be oriented by pultrusion or by fabricating the composite from unidirectional layers of uncured material, commonly called "prepreg." A bidirectional layer, or fabric, is also commonly used. An example of unidirectional layers is shown in Figure 4-1.

(b) In most laminates, it is desirable to have a variety of fiber orientations so that the desired directional properties can be obtained. The various unidirectional layers are stacked together to form a laminate. An example of this is shown in Figure 4-2 for a four-layer laminate.

(c) Various stacking sequences (or "lay-up") can be chosen. If all the fibers are chosen to be in one direction, then the maximum possible strength for this composite will be obtained in that direction. However, a unidirectional composite will have a very low strength transverse to the fiber direction.

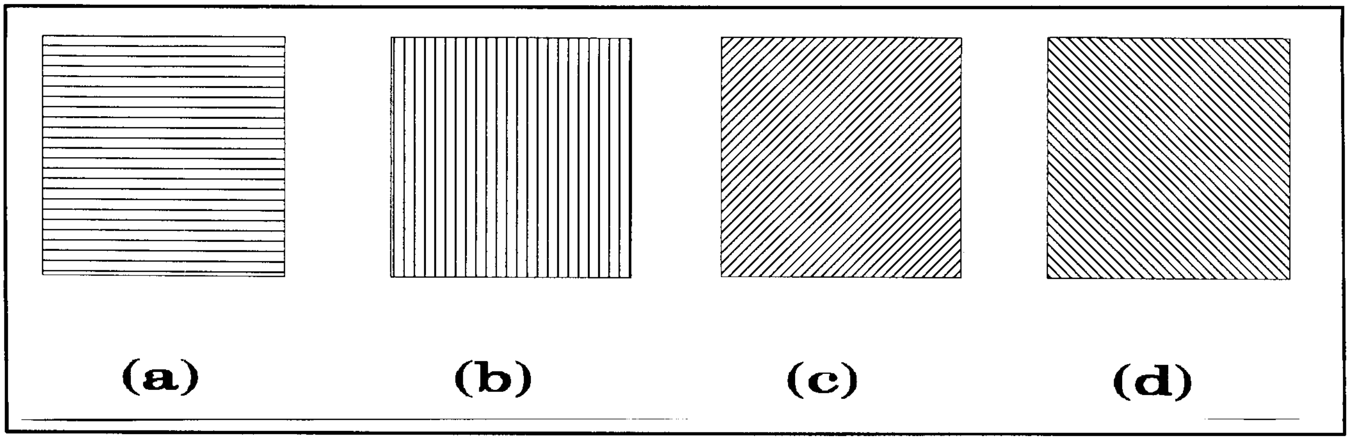

Figure 4-1. Unidirectional plies are used to fabricate a multidirectional composite
(a) Fibers are at 0°.
(b) Fibers are at 90°.
(c) Fibers are at +45°.
(d) Fibers are at -45°.

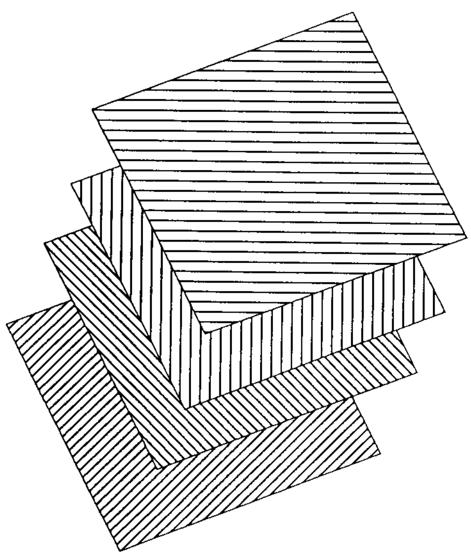

Figure 4-2. Unidirectional plies of various orientations are stacked together to make a laminate which has the desired properties

(d) Since fiber orientation dramatically affects strength and stiffness, a notation system has been developed to indicate the orientations in question. For example a 16-ply laminate that has all the fibers in the same direction is typically represented by:

$$[0_{16}]$$

The first number indicates the fiber orientation in degrees. The subscript number following the zero lists the number of layers of that particular orientation. This lay-up would have very high strength in the 0-degree direction, but very low strength in the 90-degree direction.

(e) A 16-ply laminate that has half of the fibers in one direction and half of them in a perpendicular direction could be represented by:

$$[0_4/90_8/0_4]$$

Since this lay-up is also symmetric, an alternate shorthand notation could be used. This lay-up could be written as shown below (where the S indicates that the axis of symmetry is the last ply shown in the listing):

$$[0_4/90_4]_S$$

This lay-up has the same tensile strength in both 0- and 90-degree directions, but its strength is about one half of the unidirectional lay-up in the fiber direction. In all these lay-ups, the order of the angles also represents the stacking sequence of the plies. In the one shown above, there are four 0-degree plies at both edges, surrounding a center region of eight 90-degree plies. This particular lay-up is symmetric about the center, which is usually desired in composite applications. This lay-up would tend to have a very low value of Poisson's ratio. Its shear stiffness would be the same as that for a unidirectional lay-up.

(f) If the shear stiffness needs to be maximized, then it would be most desirable to have all the fibers in the

45- or -45 degree directions. This lay-up could be written as:

$$[-45_4/45_8/-45_4]$$

Poisson's ratio for the lay-up shown is usually rather large, and for some materials it can be greater than one.

(g) One additional example lay-up should be shown. This is one in which there are equal numbers of 0-, 45-, -45-, and 90-degree plies arranged symmetrically. An example of this for a 16-ply laminate would be:

$$[0_2/45_2/-45_2/90_2]_S$$

This particular lay-up will have intermediate values for both longitudinal and shear stiffnesses. This laminate is also considered to be planar quasi-isotropic in that it will macroscopically behave as if it were an isotropic material.

(h) Historically, the quasi-isotropic lay-up was the most common one used. It is easy to design with, for its properties are the same in all planar directions. However, it does not take into account the great strength available if most of the fibers are in the same direction. It is now more common to orient the majority of the fibers in the primary load direction while retaining some plies in the other directions.

(4) Hybrid composites

(a) Hybrid composites are composites modified by the addition of another material to change their properties. A hybrid fiber-based composite could be one that is composed of an epoxy resin, carbon fibers, and glass fibers. This is an example of what might be done when the designer needed to have a composite material that was stiffer than what could be obtained from a glass-based composite but did not want to incur the additional cost to make it an all-carbon-fiber composite. By adding some carbon fibers the stiffness of the glass-fiber-dominated composite material is increased. Through hybrid composites, it is possible to tailor the stiffness, strength, and ductility of the composite to end-use requirements.

(b) A hybrid composite could also be a mixture of particle and fiber reinforcement. An example of this has been used with graphite/epoxy systems. The epoxy resin is rather brittle. In an effort to make the resin more ductile, some engineers have added rubber particles to the resin. These particles bond poorly with the resin, and act to form dull-tipped cracks. This will increase the toughness of the composite. This might be called particle weakening rather than particle strengthening. The fibers are in this system to make it strong, and the rubber particles are added to the resin to make it more ductile. Hybrid composites can also be used to improve durability. An outer layer of carbon fibers can be used to protect a core of glass fibers from breaking due to impact loads.

c. *Composites versus traditional civil engineering materials.* Civil engineers have experience designing with traditional materials that behave similarly to modern FRP materials. This should encourage the engineer who is somewhat apprehensive about designing with FRP materials. Two examples shown below are reinforced concrete and timber.

(1) Reinforced concrete. Steel-reinforced concrete is a classic example of a hybrid composite material. Its components of cement paste, aggregate, and steel all combine to produce mechanical properties that are considerably different from those of any of its components. Steel-reinforced concrete is very anisotropic in its strength. This is also true of most oriented fiber-based composites. When designing with steel-reinforced concrete, the engineer needs to understand how loads are transmitted through the system. The reinforcing layout that will provide very high strength in the primary reinforcing direction will also result in comparatively low strength transverse to the reinforcing direction. To safely use such anisotropic materials requires that the engineer understand the state of stress created in the system. An unanticipated load transverse to the reinforcing bars could produce a disastrous failure.

(2) Wood. Wood is a natural composite with anisotropic properties. Because of its grain structure its strength in one direction may be very much different from its strength in another direction. This type of difference is very typical of the anisotropic properties of modern composite materials. An engineer who has successfully designed a timber-based structure has designed with a material that behaves similarly to a composite material.

(3) Materials properties comparison. To better understand the differences between properties of a typical structural steel and those of FRP's such as glass/polyester and graphite/epoxy composite materials, examples of their properties are shown in Table 4-1. In evaluating composite materials the engineer should use their specific modulus and specific strength. While the steel is the stiffest material, the graphite/epoxy system has a specific stiffness that is about 1.75 times greater than that of steel.

Table 4-1
Contrasting Properties of Steel and Composite Materials

Material	Modulus GPa (10^6 psi)	Strength MPa (10^3 psi)	Density g/cm^3 (lb/ft^3)	Specific Modulus[3] GPa (10^6 psi)	Specific Strength[3] MPa (10^3 psi)
Steel[1]	207 (30.0)	248 (35.9)	7.87 (490)	26.3 (3.81)	31.5 (4.57)
Glass/ polyester[2]	27.1 (3.93)	287 (41.6)	2.13 (133)	12.7 (1.84)	135 (19.58)
Graphite/ epoxy [2]	70.3 (10.2)	683 (99.0)	1.61 (100)	43.7 (6.34)	424 (61.48)

[1] This is a typical grade of structural steel.
[2] The composite properties are dependent upon the stacking sequence chosen. These properties represent a quasi-isotropic lay-up of the composite material. Typical industry materials were chosen. See Table 5-4 for effects of ply orientation.
[3] In order to present the specific modulus and specific strength in more traditional units, the values of modulus and strength were divided by the specific gravity of the material, rather than by its density.

Although the steel is about 9 times as stiff as the glass/polyester, it is only twice as stiff on a per weight basis. In terms of specific strength, the glass/polyester is about 12 times stronger than steel, and the graphite/epoxy is about 13 times stronger than steel.

4-3. Types of Composite Components

FRP composites consist of fibers enclosed in a polymeric matrix. Within this group there are many different types of resins and fibers that could be chosen. Several examples of these are shown in the following paragraphs.

a. Resins.

(1) There are two broad families of resins that are commonly used in composite materials. They are thermoplastics and thermosets. A thermoplastic material can be remolded into a different shape through the application of heat and force. A thermoset cannot be remolded after it has been cured. At the present time thermosets are more commonly used in FRP's. Most references to resins are for thermoset resins.

(2) Thermoplastics are composed of long hydrocarbon chains that are not chemically bonded. This system will allow one chain to slide with respect to the adjacent chain. This will produce a material that is very ductile and of relatively low strength. Thermoplastics have less resistance to elevated temperatures than thermosets. Examples of thermoplastics are polyethylene, polystyrene, polypropylene, polyetheretherketone (PEEK), polyvinyl chloride, and the acrylics.

(3) In contrast to a thermoplastic, a thermoset is a set of hydrocarbon chains where there are covalent bonds between the chains. These bonds form, or set, at higher temperatures. This produces a three-dimensional network polymer that can be very hard, brittle, and strong. The strength level can be controlled to some extent by the amount (or concentration) of these bonds between the chains. The more of these bonds between chains (called crosslinks), the stronger will be the polymer. This type of polymer cannot be reformed once cured or set. If a thermoset is reheated (in an attempt to reform it), it is likely that more crosslinking will occur, which will make it even stronger. If too much heat is applied it will decompose. Two common examples of thermosets are epoxies and polyesters. In some situations, where a higher temperature capability is required, phenolic resins are used.

(4) Sometimes the thermoset is too brittle to be easily used. Additives can be introduced into the resin to make it more ductile. As mentioned earlier, one method to accomplish this would be to add rubber particles to the thermoset. This could produce what is commonly called a toughened epoxy.

(5) Polymeric resins will absorb moisture. Since many applications are in contact with water (at least some of the time), the effect of moisture on the composite needs to be examined before it is put into place. The designer needs to evaluate each application to determine if the moisture absorption of the composite will be a problem in that specific situation.

(6) Thermosets are the most widely used resin for the type of applications that will be implemented for civil engineering structures. Because thermosets are of basic importance to these types of structures, discussion throughout the remainder of this ETL will be primarily about thermoset resins.

b. Fibers. A variety of types of fibers are used in composite materials. The fibers need to be stronger and stiffer than the polymeric matrix that surrounds them. Glass fibers are probably the most inexpensive fibers, whereas carbon fibers, are the most expensive. Aramid fibers have prices in between those of glass and carbon.

(1) Carbon (or graphite) fibers. These fibers are frequently used because of their very high strength and stiffness. Carbon fibers come in many grades which vary according to their strength and moduli. Care needs to be taken so that the fibers are well bonded to the resin matrix. This is especially true for the higher strength fibers which are smoother and form weaker bonds with the surrounding resin.

(2) Glass fibers. These fibers are frequently used as a more economical alternative to carbon fibers. They have a lower modulus than the carbon fibers; however, they cost much less. There are several types of glass fibers that are commonly used in composite materials. The most common glass fiber is E glass, but others are also available. E glass fibers have better electrical resistance than do other glass types. See Chapter 6 for a discussion of how the environment can affect glass fiber properties.

(3) Aramid fibers. These fibers are made from a high strength hydrocarbon. A common example of an aramid fiber is Kevlar. Since each one of these fibers is frequently composed of even smaller groups of fibers (to give a ropelike appearance), aramid-based composites are frequently more ductile than carbon-based composites. For example, aramid-based composites are frequently used in bulletproof vests. The aramid composite stops a projectile by deforming during the impact.

c. Sizing. Sizing refers to the coating of the individual fibers before they are mixed with the resin. Graphite fibers are frequently coated with a very thin coating of an organic-type material. This coating is commonly called "sizing" or a coupling agent. The coating will act to protect the fiber itself, which is typically very brittle and easily damaged.

d. Coatings.

(1) In this context, coatings refer to a coating of the entire structure before use (but after fabrication). The purpose of the coating is to protect the underlying resin and fibers from chemical and/or abrasive attack.

(2) Coating of the entire structure has a very different purpose from sizing. This type of coating is typically applied to protect the structure from some sort of environmental damage. A coating could be applied to protect the resin from damage by ultraviolet radiation. Some coatings can reduce the amount of moisture absorption by the structure. All polymeric resins will absorb water to some extent. If the resin can be kept physically separate from water, then it will be less likely to be damaged by moisture absorption.

4-4. Processing

There are many production methods. These methods have been discussed in the literature. Two excellent references are Ashbee (1993) and Schwartz (1984). A list of several types of fabrication and curing methods is given below.

- Hand lay-up.
- Filament winding.
- Chopped fiber spray lay-up.
- Press molding.
- Vacuum molding.
- Autoclave molding.
- Injection molding.
- Resin transfer molding.
- Pultrusion.
- Vacuum-assisted resin transfer molding.

The following discussion emphasizes methods that are used to produce structural composites. For other methods, the reader should consult the references cited above. Some of the following methods are not economical without a large volume of production.

It should be noted that pultrusion and vacuum assisted resin transfer molding are becoming the primary processes used in producing structural composites for civil engineering applications.

a. Filament winding. This method is used to apply uncured and unidirectional plies to a structure that is a simple shape, such as a plate or cylinder. The fibers are wound onto the structure in one of several ways. It could be done with groups of fibers applied by themselves. If this is the case, then the resin needs to be applied later by some other means (such as spraying). As a second method, the fibers could be pulled through a bath of the resin in order to have the proper amount of resin. A third alternative is for the machine to lay down strips of prepreg, which are fibers already impregnated into an uncured resin. Once the fiber resin structure is in place, the structure must be cured.

b. Press molding. This method is used after the uncured composite has been laid up using filament winding or some other technique. The composite part is put into the press and an external load and elevated temperature are applied. The pressure and temperature act to promote chemical bonding between layers and within individual layers. This method is commonly used for simple shapes, such as flat plates.

c. Vacuum bag molding. This is an alternative method that is used to press the individual plies together to get good bonding. The entire part is placed inside a flexible bag. A vacuum is then applied to the inside of the bag. The external air pressure then acts to push the plies together. The vacuum also acts as a means to remove the volatiles that form during the curing process. This method will work if the applied external pressure does not have to be very high in order to adequately push together the layers of the composite material.

d. Autoclave molding. This method uses a furnace that can cure the composite at elevated temperature and elevated pressure. It allows more complex shapes to be formed than does the press molding method. The autoclaves can be quite large. Some aircraft manufacturers have autoclaves large enough to put an entire wing or tail assembly within it, so that the entire structure can be cured at one time. This method is frequently used along with the vacuum bagging method. In this manner there is a vacuum to remove the volatiles while there can be a large external pressure applied to push the structure together.

e. Pultrusion. This is a method in which the fibers are passed through a resin bath to coat them. The resin-coated fibers are then pulled through a die that acts to push the fibers together, thereby helping to produce a composite with a high fiber volume fraction. Dies can be fabricated so that a variety of shapes can be produced. Examples of such shapes are round bars, rectangular shaped bars, and channels. Several of these shapes are shown in Figure 2-1.

f. Vacuum assisted resin transfer molding. One example of this method is SCRIMP (the trade name). SCRIMP is the acronym for the Seemann Composite Resin Infusion Molding Process. This process is similar to the traditional resin transfer mold methods, except that it requires only one tool side and a simple vacuum bag. This allows for parts to be manufactured much more simply and cheaply than if an autoclave process had been used.